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Bi-level Fuzzy Optimization Model of an Algae-Sugarcane-Based Eco-Industrial Park

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Eco-industrial parks (EIPs) are designed to serve as effective measures in mitigating resource depletion and improving the environmental footprint of industrial processes. The system implements the concept of industrial symbiosis wherein an exchange of resources is conducted among the plants to achieve mutual economic and environmental benefit. The park authority has an objective of minimizing the environmental footprints of the EIP, and each respective plant aims to maximize its annual net profit while satisfying product demand. Thus, the design of the multiple resource type exchange network within the EIP can be adopted as a bi-level fuzzy optimization model, with the park authority designated as the upper-level decision-maker. The study investigates the impact of environmental footprint limits set by the park authority in the optimal design of the resource exchange networks between the plants in the EIP. A case study involving an algae-sugarcane-based eco-industrial park is considered to demonstrate the model. The results indicate that a compromise can be achieved between the levels of decision-makers at an overall degree of satisfaction of 0.189. This suggests the feasibility of the proposed EIP model accounting for the objectives of both levels of decision-makers.

1. Introduction

With natural resources being consumed rapidly, optimizing industrial processes would not only increase system efficiency but also prolong the resource availability for future use (Shi et al., 2010). The identification and assessment of different environmental hazards have been conducted to better capture the advantages and drawbacks of technologies used in Process Integration (Čuček et al., 2011). Industrial ecology encompasses this need for symbiosis between entities. Quantitative methodologies in process integration can help facilitate the interconnections present in industrial ecology (Tan et al., 2015). A growing field of interest in industrial symbiosis is eco-industrial parks (EIP). In an eco-industrial park, material and energy exchanges are apparent; each entity partially relying on the other for operation (Liwarska-Bizukojc et al., 2009). Gibbs and Deutz (2007) further explains that an EIP operates inside the boundary of conserving natural resources and maximizing economic gains. Andiappan et al. (2015) discusses the possible advantages and disadvantages experienced by each entity when engaging in industrial symbiosis. Based on a review of literature, Boix et al. (2015) classifies that the exchanges fall into three types; water, material, and energy.
Most work focus on a single-stream network configuration. The most dominant in EIPs is the water exchange network where water distribution and minimization of freshwater use are often optimized by considering a wastewater treatment facility and its treated water discharge network (Lovelady and El-Halwagi, 2009). It has been proposed that the cooperation among EIP tenants is further induced through the introduction of an external body such as the EIP authority. The EIP authority, considered as the upper-level decision maker or leader, can impose fees and subsidies to influence the participation of the tenants (lower-level decision makers) in the exchange network (Aviso et al., 2010), and that the solution can be solved using bi-level

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optimization. Aviso et al. (2010) used fuzzy optimization to integrate the goals of the upper-level and lower-level decision-maker into a single objective. The fuzzy goals are normalized to achieve a value between 0 and 1 to represent the degree of satisfaction (λ) of each goal. A value of $\lambda = 0$ indicates that the goal is not met, a value of 1 indicates full satisfaction while any partial satisfaction of the goal corresponds to a value of λ between 0 and 1. With multiple potentially conflicting objectives, the max-min aggregation method produces the best compromise solution by maximizing the least satisfied member's λ (Zimmermann, 1978).

Although the EIPs have advanced through the recent years (Heeres et al., 2004), their development has introduced barriers in some areas (Lambert and Boons, 2002) and there is limited to no literature in incorporating a fuzzy bi-level optimization model on EIPs with multiple resource type exchanges. In this paper, a bi-level fuzzy optimization model for an algae-sugarcane-based EIP is developed to investigate the interaction between the upper-level and lower-level decision-makers under environmental and economic objectives. In addition, resource exchanges of multiple types within the EIP will be considered. The rest of the paper is organized as follows. Section 2 discusses the problem to be addressed by the study. Section 3 explains the bi-level fuzzy optimization model. Section 4 elaborates the case study upon which the optimization model is implemented. Finally, conclusions and recommendations for future studies are summarized in Section 5.

2. Problem Statement

The study investigates the optimal exchange of streams between plants which are situated in the same EIP under the policies and regulations imposed by the government. There are N participating plants in the EIP and M number of material or energy streams which can be exchanged. Products may be utilized within the EIP or sold to external clients. Similarly, material or energy demands may be sourced within the EIP or from an external supplier. The park authority acts as the upper-level decision-maker and aims to minimize K number of environmental footprints in the EIP. On the other hand, of the participating plants (lower-level decision-maker) intend to maximize their individual profits and satisfy the demand for P number of main products. The park authority can regulate the environmental footprints by imposing footprint limits on the plants. Given that there is a complete exchange of information among the decision-makers, the problem then is to identify the optimal design of the exchange network to ensure that the lower-level optimal solution satisfies the upper-level objective.

3. Bi-level Fuzzy Optimization Model

Given the two levels of decision-makers with their respective optimization objectives, a bi-level fuzzy programming model is considered to determine a compromise between the two levels of stakeholders. The model functions in a similar manner as a static Stackelberg game with leader-follower strategy (Stackelberg, 1952). The leader takes the first action, then the followers deliver an optimal response based on the leader's decision. The strategy is as outlined by Shih et al. (1996) and proceeds as follows. Step 1, the leader first optimizes the initial system based only on his objectives. Step 2 the followers identify their optimal solution based on their objectives. Step 3, the results of these optimization models are incorporated as fuzzy limits to the respective objectives of the decision-makers in the bi-level model. Step 4, if the followers' objectives are not met, the leader iterates the set conditions to better accommodate the objectives of the followers better and satisfy their respective objectives (Aviso et al., 2010). The resource exchange network in the study is based on the source-sink network representations in Foo and Tan (2016).

The overall objective of the leader is to maximize its λ^* Eq(1), where D is any large number. Eq(1) corresponds to minimizing the environmental footprints of the EIP as given in Eq(2) – Eq(3). The formulation of the objective function is adapted from the work of Javadian et al. (2009) to ensure that the fuzzy solution is Pareto optimal. Similarly, the followers intend to maximize the satisfaction of their objectives Eq(4) – Eq(5) which depend on meeting product demand - Eq(6) and Eq(7) - and plant profit goals - Eq(8) subject to material and energy balances - Eq(9).

Depending on the operation of participating plants in the EIP, material and energy streams maybe produced internally, imported from an external source or exported if there is a surplus - Eq(10) – Eq(13). A plant generates revenues from selling products within or outside the EIP and incurs costs for input expenses obtained from within or outside of the EIP - Eq(14) – Eq(16). The lower-level model is constrained by the environmental footprint goal of the upper-level decision-maker Eq(17).

Table 1: Nomenclature

Parameters	Variables	
q_{kj} – environmental intervention k of plant j	λ^* - degree of satisfaction of leader's objective	y_i – net output of EIP for stream i
Z_k^L, Z_k^U – lower and upper fuzzy limit for footprint k	λ^{**} - degree of satisfaction of follower's objective	y_i^{exp} – amount of stream i exported from EIP
a_{ij} – technical coefficient of stream i in plant j	$\lambda^3{}_k$ – footprint k degree of satisfaction	y_i^{imp} – amount of stream i imported by EIP
C_i^{int}, C_i^{imp}, C_i^{exp} – unit cost of stream i for internal consumption, import and export	z_k – environmental footprint k of EIP	$Profit_j$- profit of plant j
$y_{a,i}, y_{b,i}$, $y_{c,i}$, $y_{d,i}$ – fuzzy limits of stream i	b_i – binary variable for stream i	$\lambda^1{}_i$ –degree of satisfaction for demand of stream i
y_i^L, y_i^U – lower and upper limit for the import/export of stream i	d_{ij} – binary variable for stream i in plant j	$\lambda^2{}_j$ –degree of profit satisfaction of plant j
AP_j^L, AP_j^U –fuzzy limits for profit of plant j	x_j – operating level of plant j	

Leader's objective:

$$\max \lambda^* + \frac{1}{D}\left(\sum_{k=1}^{K} \lambda_k^3\right) \tag{1}$$

$$z_k = \sum_{j=1}^{N} q_{kj} x_j \qquad \forall k \in K, \forall j \in P \tag{2}$$

$$z_k \leq Z_k^U - \lambda^3 (Z_k^U - Z_k^L) \qquad \forall k \in K \tag{3}$$

Follower's objective:

$$\max \lambda^{**} + \frac{1}{D}\left(\sum_{i=1}^{P} \lambda^1{}_i + \sum_{j=1}^{N} \lambda^2{}_j\right) \tag{4}$$

Subject to:

$$\lambda^{**} \leq \lambda^1{}_i, \lambda^2{}_j \tag{5}$$

$$y_i = y_{a,i} + \lambda^1{}_i \left(y_{b,i} - y_{a,i}\right) \qquad \forall i \in P \tag{6}$$

$$y_i = y_{d,i} - \lambda^1{}_i \left(y_{d,i} - y_{c,i}\right) \qquad \forall i \in P \tag{7}$$

$$Profit_j = AP_j^L + \lambda^2{}_j (AP_j^U - AP_j^L) \qquad \forall j \in M \tag{8}$$

$$\sum_{j=1}^{N} a_{ij} x_j = y_i \qquad \forall i \in P \tag{9}$$

$$y_i + (1-b_i) y_i^{imp} - b_i y_i^{exp} = 0 \qquad \forall i \in P \tag{10}$$

$$b_i \in \{0,1\} \qquad \forall i \in P \tag{11}$$

$$y_i \leq b_i y_i^U \qquad \forall i \in P \tag{12}$$

$$y_i \geq -(1-b_i) y_i^L \qquad \forall i \in P \tag{13}$$

$$Profit_j = \sum_{i=1}^{P} \left(a_{ij} x_j \left(C_i^{int} b_i + C_i^{exp} (1-b_i)\right) + y_i^{exp} d_{ij} \left(C_i^{exp} - C_i^{int}\right)\right) \qquad \forall j \in M \tag{14}$$

$$-(1-d_{ij}) D \leq a_{ij} x_j \leq d_{ij} D \qquad \forall i \in P, \forall j \in M \tag{15}$$

$$d_{ij} \in \{0,1\} \qquad \forall i \in P, \forall j \in M \tag{16}$$

$$\sum_{j=1}^{N} q_{kj} x_j \leq z_k^* \qquad \forall k \in K \tag{17}$$

Bi-level objective function:

$$\max \lambda + \frac{1}{D}\left(\sum_{i=1}^{P} \lambda^1{}_i + \sum_{j=1}^{N} \lambda^2{}_j + \sum_{k=1}^{K} \lambda^3\right) \tag{18}$$

The bi-level model integrates the objectives of both the leader and the follower using Eq(18). The model is solved using LINGO 16.0.

4. Case Study

Given the potential of microalgae in biofuel production, efforts are being undertaken to improve its commercial viability and sustainability (Ubando et al., 2015). Measures undertaken to achieve the said objective include the implementation of the technology in EIPs (Ubando et al., 2015) as well as co-location with sugar mills (Moncada et al., 2014). An algae-sugarcane-based EIP is considered in the study, based on processing data for algae from Ubando et al. (2015) and sugarcane from Moncada et al. (2014). The plants involved in the EIP include: 1) an integrated microalgae-to-biodiesel plant (IMBP), 2) an algae-based ethanol plant (ABEP), 3) a molasses-based ethanol plant (MBEP), 4) a wastewater treatment plant (WWTP), and 5) a sugar mill with co-generation (SMCG). The technology coefficients (a_{ij}) in Table 2 summarizes the input (negative entries) and output (positive entries) streams of each plant together with the corresponding carbon dioxide emission. Water use in the EIP may utilize treated water from the WWTP or fresh water obtained from an external source. Water footprint is thus obtained based from total freshwater use. Table 2 also indicates the unit price of the streams which are reduced by 30 % if the exchange is internal in the EIP. The main products of the EIP are: 1) biodiesel, 2) ethanol, 3) treated water, and 4) sugar. As for molasses, its price is derived from the work of Aazim (2013). To reduce freshwater consumption, the plants can use treated water priced at 0.009 US$/kg (Fort Worth, 2017). Freshwater is priced at 0.001 US$/kg. Each plant intends to meet exogenously defined fuzzy goals for profit and products while the park authority intends to meet exogenously defined fuzzy goals for environmental footprint. In real-life, these limits may be obtained from an assessment of company goals and park performance. For this case, the fuzzy goals for profit are shown in Table 3, product demands in Table 4 and environmental footprint in Table 5.

Table 2: Process matrix of the algae-sugarcane-based EIP

Products	IMBP	ABEP	MBEP	WWTP	SMCG	Price	
Microalgal Culture (kg/s)	-0.0097	0	0	0	0	0.78	US$/kg
Utility Water (kg/s)	-67.0	-1.96	-19.2	1	-1.2	0.009	US$/kg
Power (MW)	-60.4	-0.8	-0.026	-0.01	13.7	0.03	US$/MJ
Heat (MW)	-129.8	-0.03	-15.5	0	8.9	0.02	US$/MJ
Ethanol (kg/s)	-0.11	1.0	1.0	0	0	6.50	US$/kg
Biodiesel (kg/s)	1.0	0	0	0	0	6.24	US$/kg
Algal Biomass (kg/s)	0.66	-4.9	0	0	0	0.47	US$/kg
Molasses (kg/s)	0	0	-2.2	0	0.6	0.14	US$/kg
Wastewater(kg/s)	0	0.2	19.2	-2.5	8.2	0.002	US$/kg
Sugarcane (kg/s)	0	0	0	0	-9.8	0.04	US$/kg
Sugar (kg/s)	0	0	0	0	1	0.42	US$/kg
Net CO_2 Emission (kg/s)	13.1	15.5	1.0	0	2.7	-	

Table 3: Exogenously defined annual profit targets for each plant in the EIP in M US$/y

Plant	AP^L	AP^U
IMBP	188.00	258.90
ABEP	19.30	96.20
MBEP	237.40	334.60
WWTP	3.40	4.10
SMCG	87.00	103.70

Without the intervention of the park authority, the EIP can consume up to 350 kg/s of freshwater, which is provided by an external source, and generate 98 kg/s of CO_2. However, it is possible to reduce freshwater consumption up to 275 kg/s and CO_2 to 77 kg/s.

Table 4: Exogenously defined product demand limits

Products	y^a	y^b	y^c	y^d
Biodiesel (kg/s)	4.0	4.3	4.5	5.1
Ethanol (kg/s)	1.7	3.2	3.2	6.2
Sugar (kg/s)	5.2	5.8	6.3	7.0

Table 5: Exogenously defined footprint limits of the algae-sugarcane-based EIP

Footprints	z^L	z^U
Carbon Dioxide (kg/s)	76.8	94.6
Freshwater Consumption (kg/s)	275.2	316.5

A summary of the results for optimizing the leader's objective, the follower's objective and the bi-level model is shown in Table 6. The results show how the EIP performance can vary when control over the operational objectives shift between the park authority and the plants involved. Given the conflicting nature of the respective objectives of the decision-makers involved, there is difficulty in simultaneously satisfying the said objectives. Through a bi-level formulation of the optimization problem, a satisficing or near-optimal solution can be achieved with tolerances being given to the respective objective functions and constraints of the decision-makers involved. As observed in Table 6, the results indicate that a compromise solution is feasible between the two-levels of decision-makers.

When the park authority is in full control, the environmental objectives are almost completely addressed with a degree of satisfaction of 0.987. On the other hand, the follower's objective results in environmental footprints beyond the limits of the park authority. The yielded freshwater use and CO_2 emission exceed their upper limits by 8 % and 2 % . The individual profit goals of the plants have degree of satisfaction values of at least 0.479. However, if the bi-level model is implemented, freshwater use and CO_2 emission can be reduced by 10 % and 8 % respectively. Even with this reduction, the plants are still able to achieve their profit targets with the SMCG plant reaching a 0.882 degree of satisfaction and the IMBP plant having a degree of satisfaction of 0.525. The bi-level model reaches a degree of satisfaction of at least 0.513 with respect to the individual profit goals of the involved plants. This indicates that the solution from the bi-level formulation can deliver more equitable degree of satisfaction values among the individual profit targets of the involved plants as compared to the results obtained from the follower's objective. This solution utilizes water both from the external source (freshwater use) and from the WWTP. Treated water use is 36.96 kg/s. In addition, the heat and power demand of the EIP is partially supplied by the SMCG. The ethanol requirement of the IMBP is completely satisfied by the MBEP. The algal biomass of the IMBP is delivered to the ABEP, thus meeting biomass demand of the latter. Other streams which are imported from an external source include the microalgal culture (0.043 kg/s), power (177 MW), heat (549 MW) and sugarcane (67.3 kg/s).

Table 6: Summary of results

Footprints	Leader's objective	Follower's objective	Bi-level formulation
Biodiesel (kg/s)	4.00	4.98	4.48
Ethanol (kg/s)	1.70	1.99	1.98
Sugar (kg/s)	6.80	6.86	6.87
CO_2 (kg/s)	77.04	96.07	88.48
Freshwater use (kg/s)	275.76	342.35	308.69
λ	0.987	0.196	0.189
λ^1	-	0.196	0.189
λ^2	-	0.479	0.513
λ^3	0.987	-	0.189

5. Conclusion

The success of an EIP is dependent on the cooperation of the stakeholders who may have objectives which conflict with one another. A bi-level fuzzy optimization model is developed to determine the optimal operating condition of the resource exchange network of a biomass-based EIP that satisfies both overall footprint goals of the park authority, as well as the profit goals of each plant. The results of the study can give insights on how regulatory mechanisms can be developed to stimulate green initiatives in industry. It also highlights how the respective optimal configurations of the EIP under complete leader or follower control can vary from each other. Furthermore, it shows to what extent does the compromise solution satisfy the respective objectives of the two different levels of decision-makers. In addition, it presents a supplementary negotiation framework that permits stakeholders with different hierarchies of authority to reach an agreement despite the possibility of their objectives conflicting with one another.

For future works, the model can be extended by incorporating product demand and market price uncertainty to capture the impact of changing market behaviours. In addition, purity level of treated water can also be taken into consideration since certain processes can only operate under a range of contaminant concentration. The impact of the introducing additional plants into the EIP can also be explored. Different environmental metrics such as land and nitrogen footprint can be incorporated in future studies.

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